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Report No. 252
June 1984

This research was supported by the Engineering Psychology Programs, Office of Naval Research, Contract N00014-81-C-0591, Work Unit Number NR 197-073 and by BRSG Grant #RR07013-14 awarded by the Biomedical Research Support Program, Division of Research Resources, NIH. Center for Research on Judgment and Policy, Institute of Behavioral Science, University of Colorado.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: CRJP 252	2. GOVT ACCESSION NO.: AD-A142 866
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): The Relative Efficacy of Intuitive and Analytical Cognition: A Second Direct Comparison	5. TYPE OF REPORT & PERIOD COVERED: Technical
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Kenneth R. Hammond, Robert M. Hamm, Janet Grassia and Tamra Pearson	8. CONTRACT OR GRANT NUMBER(s): N00014-81-C-0591
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Center for Research on Judgment and Policy, Institute of Cognitive Science, University of Colorado, Boulder, CO 80309	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NR 197-073
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, 800 North Quincy Street, Arlington, VA 22217	12. REPORT DATE: June 1984
	13. NUMBER OF PAGES: 85
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release: Distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

intuitive/analytical, expert judgment, judgment policy, safety, aesthetic judgment, task effects

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(See reverse side)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT

In contrast to the usual indirect comparison of cognitive activity with a normative model, direct comparisons were made between the relative efficacy of highway experts' use of analytical, quasi-rational and intuitive cognition on three different tasks, each displayed in three different ways. Indices were developed for measuring the location of each task condition on a continuum ranging from intuition inducing to analysis inducing and for measuring the location of each expert's cognition on a continuum ranging from intuition to analysis.

Individual analyses of each expert's performance over the nine conditions showed that the location of the task on the task index induced cognition to be located at the corresponding region on the cognitive continuum index. In contrast to results found with the customary indirect comparisons, intuitive and quasi-rational cognition frequently out-performed analytical cognition in terms of empirical accuracy. The large but infrequent errors of analytical cognition did not wholly explain its lower performance. Judgmental accuracy was related in part to the degree of correspondence between the task location and the location of the experts' cognitive activity on the cognitive continuum.

Research in the field of judgment and decision making often compares the rationality of a person's intuitive judgments under uncertainty with analytically derived answers produced by a formal model such as Bayes' Theorem, a multiple regression equation, or other rules from the conventional probability calculus (for reviews see Einhorn & Hogarth, 1981; Hammond, McClelland, & Mumpower, 1980; Jungermann, 1983; Kahneman, Slovic, & Tversky, 1982; Pitz & Sachs, 1984). Such comparisons are indirect: they compare a person's intuitive efforts with person-independent operations. That is, they compare a person's intuitive processes and judgments with those of an analytically-derived rule or equation put forward as a standard of rationality. Indirect comparisons are undeniably important, but they are necessarily restricted in three ways. First, because indirect comparisons evaluate intuition with respect to a standard of rationality, researchers must choose some standard from among the many offered. But agreement on which standard of rationality is correct has never been achieved. The choice of any standard, therefore, is subject to dispute, and any conclusions drawn regarding the failure of subjects to achieve the standard chosen are sure to be criticized by those who prefer a different standard (as indeed they have been; see Cohen, 1981; Kyberg, 1983; also Einhorn & Hogarth, 1981).

Second, the results of indirect comparisons cannot fail to show that analytical cognition is equal or superior to intuitive cognition because analytical models, however chosen, provide the standard to be achieved by persons. If intuition offers an advantage over analysis, as many have argued it does, its putative advantage cannot be demonstrated in indirect comparisons because the analytical model provides a ceiling. Therefore it is not altogether surprising that populational studies find that few persons' intuitive efforts achieve the standard (Kahneman et al., 1982) and none exceed it.

<u>Third</u>, when indirect comparisons are made, the analytical models are always provided with all the correct (and only the correct) substantive information each model requires. And such models are (almost) always executed without error--at least in academic journals. In practice, however, analytical cognition, as distinct from models of it, is vulnerable to <u>substantive</u> failures (insufficient information, incorrect information, incorrect substantive theory, insufficient time) and <u>procedural</u> failures (incorrect assignment of numbers to the symbols of the equation, computational errors, use of an incorrect model). In short, valuable as work on indirect comparisons may be, these restrictions prevent them from informing us about the relative efficacy of intuitive and analytical cognition as practiced by persons.

Therefore <u>direct</u> comparisons between a person's use of intuition and the same person's use of analysis are also needed. Direct comparisons will inform us about the <u>relative efficacy</u> of these modes of cognition in terms of empirical achievement or correctness. Comparisons of relative efficacy, however, require the presence of an empirical criterion with which judgments are compared, rather than a standard of rationality. When such criteria are available direct comparisons enable us to address the age-old question: Does a person's intuitive or analytical cognition produce more empirically accurate answers? (See Einhorn & Hogarth, 1981, for parallel remarks; see also their stimulating discussion of "accuracy vs. truth", 1982.) The work described below makes direct comparisons of the relative efficacy of intuitive and analytical modes of cognition in the context of a study of expert judgment.

Premises

Our approach rejects the traditional dichotomy between intuition and analysis. It is based on the premise that both cognitive processes and task conditions can be arranged on a continuum that runs from intuition to analysis (Hammond & Brehmer, 1973, p. 340; see also Hammond, 1955, 1966, 1982; Brunswik, 1956; Goldsberry, 1983). Furthermore, once cognitive processes are defined in terms of their location on a cognitive continuum, they will be found to interact in predictable ways with various task conditions located on a similar continuum. Goldsberry (1983) found confirmatory results in the initial test of that prediction. The present study extends the test of the validity of that prediction.

The above premise and prediction follow directly from the Brunswikian tradition of systematically examining task characteristics as determiners of behavior, a tradition that is receiving increasing support from contemporary researchers. For example, Beach and Mitchell (1978), Einhorn and Hogarth (1981), Payne (1982), and Howell and Kerkar (1982) have reiterated the need for further systematic analysis of the effects of task properties on cognitive processes. Hoch and Tschirgi (1983) provide an excellent example of the use of the Brunswikian framework for comparing cognitive activity with an analytical model of deductive reasoning. They show that the "confirmation bias" produced when subjects attempt to solve deductive problems presented in abstract form (Wason & Johnson-Laird, 1972) largely disappears when the task is permitted to include cue redundancy (an important aspect of Brunswik's representative design), thus at once restricting the previous over-generalization and extending our knowledge to tasks representing those more likely to be encountered.

Theoretical Background

Direct (and indirect) comparisons of different modes of cognition require not only a theory of cognition but a theory of context as well, unless the cognitive theory claims universal generality over tasks. Since we reject the traditional premise of a dichotomy between intuition and analysis and posit a continuum instead, the continuum theory must, first, provide a set of descriptive terms that will make it possible to denote the location of a person's cognitive activity on the cognitive continuum; second, provide a set of descriptive terms that will enable us to denote the location of a task on a task continuum according to the hypothesized ability of the task to induce cognition to be activated at a predicted region on the cognitive continuum; and third, indicate the consequences of the correspondence between task location and cognitive location for various behaviors, such as the accuracy of judgments. Without an attempt to provide a priori a reasonably complete set of descriptors of both task properties and cognitive properties, any cognitive theory is apt to provide predictions of behavior difficult to falsify.

Descriptors for Modes of Cognition

Researchers in cognition almost never explain what they mean by intuition, although they take great pains to differentiate precisely among formal, analytical models of cognition. As a result, it is customary to define intuition in terms of what it is not. Brooks (1978), for example, compares "analytical and nonanalytical concept formation", and Beach and Mitchell (1978) refer to "nonanalytical strategies" (emphasis ours). And Kahneman and Tverksy (1982) indicate that "a judgment is called intuitive if it is reached by an informal and unstructured mode of reasoning, without the use of analytical methods or deliberate calculations" (emphasis ours). Even philosophers (e.g., Cohen, 1981) who criticize psychological research on

judgments fail to say what they mean by intuition. In an effort to specify meaning, we provide a list of descriptors that apply to intuition as well as analysis.

According to cognitive continuum theory, intuition and analysis can be distinguished by the degree of the subject's: (a) cognitive control (in intuition, low; in analysis, high); (b) rate of data processing (in intuition, rapid, i.e., as brief as microseconds; in analysis, slow, i.e., as long as hours, days, or years); (c) conscious awareness of process (in intuition, low; in analysis, high); (d) type of organizing principle (in intuition, a weighted average; in analysis, other, task-specific principles); (e) type of error (in intuition, normally distributed; in analysis, few, but large errors); (f) type of confidence (in intuition, confidence in answer but not method; in analysis, confidence in method, not answer). (For further distinctions, see Hammond, 1982.) The compromise form of cognition, quasi rationality or "common sense," lies in between these polar forms of cognition, and thus includes properties from both types of cognition. Some applications of quasi rationality will lie closer to intuition, some closer to analysis. (See Brunswik, 1956; Hammond, 1955, 1966, for early discussions of "compromise" and quasi rationality; also Hammond 1982, for a comparison of quasi rationality with "bounded rationality," introduced by Simon, 1957, pp. 196-206.; see Wyer, 1976, for an example of compromise among probability estimates; also Payne, 1976)

Descriptors for Task Conditions that Induce Different Modes of Cognition

In his 1982 review, Payne indicates that research shows that "decision making...is highly contingent on the demands of the task" (p. 382). Here we provide a list of task properties predicted to induce different forms of cognition. If subjects are not provided with feedback, the task properties that differentially induce intuition and analysis include: (a) number of cues available (in intuition, large [> 5]; in analysis, small); (b) the order in which cues are displayed (in intuition, simultaneous; in analysis, sequential); (c) the type of cue measurement required (in intuition, perceptual; in analysis, objective, as with instruments) and the reliability of this cue measurement (in intuition, low; in analysis, high); (d) cue distribution characteristics (in intuition, continuous, highly variable, normally distributed; in analysis dichotomous, valued in terms of specific numbers, distributions unknown); (e) redundancy among cues (in intuition, high; in analysis, low); (f) the degree of a priori decomposition of the task for the subject (in intuition, low; in analysis, high); (g) the uncertainty of the criterion (in intuition, high; in analysis, low); (h) the degree of nonlinearity in the correct environment model (in intuition, low; in analysis, high); (i) the extent to which the cues are combined, in the correct environmental model, with equal weights (in intuition, high; in analysis, low); and (j) the availability to the subject of an organizing principle (in intuition, low; in analysis, high). (See Hammond, 1982, for further elaboration.) In her research, Goldsberry (1983) manipulated (a) number of cues, (b) time, (c) availability of an organizing principle, and (d) complexity of the principle as a means of inducing intuition and analysis.

Degrees of quasi rationality are induced to the extent that a task contains properties from both polar task conditions, or properties whose values lie between the polar values.

Inducement of Cognitive Properties

A specific theoretical prediction is that each set of task properties will induce corresponding cognitive properties. For example, if the task presents (a) many redundant cues with (b) continuous values displayed (c) simultaneously that must be measured (d) perceptually, and for which the subject has available no (e) explicit principle or method for organizing cues into a judgment, then the subject will employ intuitive cognition. That is, subjects will observe and use many redundant cues (because of their simultaneous display), measure their values perceptually (because there is no alternative), and therefore, subjective cue values will be unreliably assigned to each cue, a circumstance reinforced by the continuous nature of the cues, thus leading to inconsistency or low cognitive control. Moreover, if the subject cannot employ the appropriate organizing principle either because s/he knows of none, or time will not permit its application, then a weighted averaging method of organizing the information will be implicitly applied.

We predict that a weighted averaging or simple summation organizing principle will be used because these are the most robust of all aggregation methods (Dawes & Corrigan, 1974). Robustness means high accuracy in spite of (a) incorrect assignment of weights, (b) poor approximations to the correct function forms between cue and criterion, and (c) poor approximation to the correct organizing principle in the task. Such robustness would provide an epistemological evolutionary advantage for any organism capable of multiple cue usage in tasks that induce intuition, particularly when time is limited. Therefore, a weighted averaging or simple summation method should be a strong

candidate for an intuitive method of organizing information under the intuition-inducing conditions described above. (See Wallsten & Budescu, 1981, who provide empirical support for a similar conceptual link between additive processes and intuitive (non-expert) cognition; see Anderson, 1981, for examples of studies in which weighted averages frequently appear and for a detailed technical treatment of "cognitive algebra"; see Brunswik, 1956, pp. 89-99, and Hammond, 1980, for a discussion of the advantages and disadvantages of intuitive cognition for survival). The rationale for the task properties that induce analysis is opposite in substance but similar in form.

The verb "induce" is used to avoid the implication of inevitability or a fully deterministic relation between task properties and cognitive properties. It is apparent that analysis can be (and is) applied to intuition-inducing tasks (e.g., if there is time) and that intuition can be (and is) applied to analysis-inducing tasks (e.g, if time is limited). Moreover, as the concept of quasi rationality implies, task conditions may include some properties from each end of the continuum and therefore some of the properties of each polar mode can be induced in a single task. Thus, tasks with properties from each pole of the continuum may induce a <u>compromise</u> between intuition and analysis. (See Brunswik, 1952, 1956; see also Hammond, 1955, 1966, and Hammond & Brehmer, 1973; Brehmer, 1978, demonstrates the role of task properties in the production of compromise in interpersonal conflict; see also Tversky & Kahneman, 1983, for the use of the concept of cognitive "trade-offs", thus implying compromise between one mode of cognition and another.)

The precise location of cognitive activity on the cognitive continuum will depend upon (a) how many and (b) which task properties are present. as well as (c) the amount of a property present. Unfortunately, we do not yet know the relative power of various task properties, however specified, to place cognitive activity at one location or an other on the continuum. Nor is it known whether one task property is essential for inducing one mode or another, or how effective various task properties are in moving cognition in one direction or the other. The study to be described below takes an initial step toward the acquisition of such knowledge. A further distinction among task conditions needs to be made, however; that concerns the surface and depth characteristics of tasks.

Differentiation between surface and depth in cognitive tasks

In contrast to the proliferation of concepts that are employed to describe the cognitive activity of organisms, the texture of tasks remains almost wholly undifferentiated, despite repeated arguments regarding its importance (see, for example, Beach & Mitchell, 1978; Einhorn & Hogarth, 1981; Payne, 1982). But Brunswik (1957) argued that:

> Both organism and environment will have to be seen as systems, each with properties of its own....Each has surface and depth, or overt and covert regions. It follows that much as psychology must be concerned with the texture of the organism...it must also be concerned with the texture of the environment (1957, p. 5).

Brunswik's distinction between surface and depth has been developed by Hammond, Stewart, Brehmer and Steinmann (1975, see p. 275) and has also been employed in problem-solving research (Simon, 1979; also see Chi, Glaser, & Rees, 1982). In both cases the term "depth" refers to the (covert) nature of the formal relationships of the variables within the task, while "surface"

refers to the (overt) display of the task variables to the subject. (See also Tversky & Kahneman, 1983, who use the terms "opaque" and "transparent" to refer to the ease with which different forms of task presentation allow subjects to see the logical character of the task.)

Congruence between surface and depth characteristics. Since both depth and surface characteristics can be located on the task continuum, they may therefore be *congruent* or *incongruent* with one another, depending on their respective locations on the task continuum. The concept of congruence may be illustrated as follows. A logical problem will by definition have covert depth properties that place it at the analysis-inducing pole of the continuum. But the overt surface materials that inform the subject about the problem may be displayed in a variety of ways, some of which may also be analysis-inducing (and thus be congruent with the depth characteristics of the task) while some may be intuition-inducing (and thus be incongruent with them). Thus, for example, the surface displays for a logical problem may be presented (in decreasingly congruent fashion) by (a) symbolic logic, (b) the languages for computer programs (c) natural languages, (d) diagrams, or (e) pictures. At the other extreme, surface displays for tasks in which depth characteristics are intuition-inducing may also vary along the intuition-analysis continuum. The overt surface materials for pictorial work of art may (in decreasingly congruent fashion) be (a) displayed visually, (b) diagrammed to show its form (as da Vinci's "Last Supper" has been diagrammed), (c) described in natural language, or (d) in the language of a computer program (in the case of computer-produced art).

Various combinations of intuition- and analysis-inducing surface characteristics are often used in both types of tasks, thus rendering them quasi-rational in character. For example, art teachers induce quasi-rational cognition when they point to various visual features of a work of art, ask students to appreciate them by use of visual perception, and then systematically verbally analyze the features that justify its classical status. An opposite example is provided by the physics teacher who displays a set of relations first in the form of an equation, and then in the form of a pictorial, schematic model. In this case the schematic model is employed to appeal, via visual perception, to intuitive cognition, thus inducing students to increase their confidence that the abstract equation is true. (Miller, 1978, describes disputes among early quantum theorists about whether visual, and thus intuitively appealing, representations of the relations among concepts should be allowed to supplement mathematical, and thus fully analytical, representations.)

Despite the long-apparent differentiation between the surface and depth characteristics of tasks, no systematic treatment of the effect of their relation has yet appeared, although it is an intrinsic, inescapable component of every cognitive task. Payne (1982, pp. 392-392), for example, describes the importance of "information display" and describes its effects, but none of the studies he reviews systematically examines various surface displays across different depth characteristics of tasks, thus leaving indeterminate the question of which aspect of the task has greater influence on decision behavior. (But see Adelman, 1981, and Brehmer & Kuylenstierna, 1980, for an examination of the effects of the congruence between task <u>content</u> and formal relations in tasks; and Pennington, 1982, for a demonstration of the role of congruence of task elements in relation to subjects' use of the representativeness heuristic; see also Hammond, 1966, for a distinction

between the formal and substantive properties of tasks.)

In the present study, we systematically vary the degree of congruence between surface and depth characteristics of tasks in terms of their locus on the task continuum. That is, we employ three tasks whose depth characteristics enable us to place (a) one at the intuition-inducing pole, (b) one at the analysis-inducing pole, and (c) one in between. We also employ three different sets of surface characteristics, or displays, for each of the three tasks (see Figure 1). The surface characteristics also were constructed so that one display included properties that placed it near the intuition-inducing pole, one display represented the properties of the analysis-inducing pole, and one represented conditions between. Since we wish to make direct comparisons of the effect of surface-depth congruence on the cognitive activity of the same subject over these task conditions, each subject was tested in all nine cells of Figure 1.

Insert Figure 1 about here

Effects of Surface-Depth Congruence on Inducement of Cognitive Activity

On the hypothesis that the effects of surface and depth characteristics are additive, inducement of any mode of cognition should be most predictable when surface and depth task characteristics are congruent, and least predictable when they are incongruent. Specifically, if both surface and depth characteristics are intuition-inducing, then all the properties of intuitive cognition should be induced. The same holds for quasi rationality and analysis. When there is incongruence between surface and depth, compromise among cognitive properties should occur and cognitive activity should be located in between.

Effects of Surface-Depth Congruence and of Mode-Task Correspondence on Achievement

Achievement should be highest when surface task properties and depth task properties are congruent and when cognitive mode corresponds to task. These hypotheses are in direct contradiction to the view generally accepted by researchers that analytical cognition is superior to intuitive cognition over all task conditions. It can be argued, however, that when the task conditions are those described above as intuition-inducing, attempts to use analysis run the risk of incurring both substantive and procedural failures, and thus intuition may outperform analysis. (For a parallel view by a philosopher, see Rosen, 1980.)

The theoretical background presented above thus provides general hypotheses (to be made specific below) regarding task properties, cognitive properties and their joint effects on behavior in a study of expert judgment. In addition, the work carried out to test these hypotheses will clarify (a) whether, in direct comparisons between analytical cognition and intuitive cognition, analysis provides a ceiling for performance, and (b) the role of error in analytical cognition.

Method

Subjects

Twenty-one expert highway engineers (male, 30-70 years of age) were chosen as subjects because of their trained capacity to engage in analytical cognition, as well as the other two modes of cognition. Each of the 21 experts volunteered approximately 20 hours to the project.

Depth Characteristics of Tasks

Three tasks were selected because we judged that their characteristics would induce each of the three modes of cognition. These tasks required predictions of (a) highway aesthetics (intuition-inducing), (b) highway safety (quasi rationality-inducing), and (c) highway capacity (analysis-inducing). Each is described in turn; objective measures are described below.

Intuition. Judgments of aesthetics were used because the depth properties of this task include many of the intuition-inducing properties indicated above. For example, there is no known algorithm for organizing aesthetic cues, and no delimited specification of which cues are relevant; indeed, there is no indication of how aesthetics-related information (whatever it may be) should be used. Consequently, judgments of highway aesthetics depend largely on the use of perceptual material provided by the visual inspection of a highway and are never arrived at by calculation. The intuition-inducing properties of this task are illustrated in the (tape-recorded) remarks of the engineers; for example, one engineer stated: "My confidence will be zero. When you get done and ask me how I did this I will say, 'I don't know.'"

Quasi rationality. Judgments of safety were used as a quasi rationality-inducing task. The depth properties of this task include some intuition-inducing properties and some analysis-inducing properties, and some properties that are midway between the two, thus placing this task between the polar cognitive modes. Although there is no established theory, algorithm, or equation for calculating the safety of a highway, and there is no clearly delimited set of cues that are officially or professionally designated for measuring or judging the safety of highways (thus allowing for some degree of intuition as described above), nevertheless there is general agreement about

what dimensions or cues (e.g., lane width) should be used, and what their functional relationships with safety are. And more or less defensible explanations can be provided for why certain dimensions should be used in the form given, thus indicating that some degree of analysis occurs. For example, one engineer stated: "I will ... select the most important points that have a tendency to constitute accidents .... probably the most important would be the curves per mile .... shoulder width is the next most important thing".

Analysis. Judgments of highway capacity were used as an analysis-inducing task because its depth properties include many of the analysis-inducing properties indicated above. That is, it is generally agreed that the capacity of a highway can be calculated using a non-stochastic, non-linear algorithm based on well known dimensions. The relations between these dimensions and capacity are well known to highway engineers, the process is analytically and technically defensible, and it is in regular use in the design of highways. Thus, for example, one engineer said: "The idea of taking a maximum capacity ... and then multiplying it by factors is the Highway Capacity Manual way of doing it. And so I knew it was a legal way to go about it, but I didn't remember the process exactly, or the numbers especially."

Surface Characteristics of Tasks

Three forms of displaying information were constructed, in accordance with cognitive continuum theory, to induce three modes of cognition within each task. Each is described in turn; objective measures are described below.

Intuition. The engineers were induced to employ intuitive cognition for each task (aesthetics, safety and capacity) by being required to judge forty two-lane rural Colorado highways from film strips representing one- to three-mile segments of these highways (see Figure 2). The film strip presentation is intuition-inducing because all the information must be processed by visual perception. Moreover, the cues displayed in the film strips are numerous, frequently redundant, and contemporaneously displayed; the values of the cues are generally continuous and normally distributed, and the cue values must be measured solely by visual examination. Furthermore, no time was provided to organize the information according to an analytical principle.

Insert Figure 2 About Here

Quasi rationality. The engineers were induced to employ quasi-rational cognition for each task by being required to judge bar graphs representing the same highway segments as in the film strips (see Figure 3). The bar graphs induce both intuition and analysis. They induce intuition because the cues are displayed visually and contemporaneously; the cues are redundant and are generally continuous and normally distributed. The bar-graph presentation also induces analysis, however, because the number of cues is reduced from a large, unknown number to a specific set (aesthetics = 8, safety = 10, capacity = 9), each cue is visually separated from the others and its numerical value is clearly indicated; and cue values are not measured perceptually, rather, they are measured by instrument and numerically presented, thus facilitating brief comparison.

Insert Figure 3 About Here

Analysis. The engineers were given the names of the same variables that were provided in the bar graph presentation for each task. They were induced to employ analytical cognition by being required to devise mathematical formulas for calculating aesthetics, safety and capacity for all two-lane rural highways. The engineers were told that although a certain amount of time had been targeted for this task, they could work until their formulas were completed. They were provided with paper, pencils, and a calculator.

Twelve engineers were required to construct their formulas without interference from the researchers ("minimal guidance"). Another six experts were required to "think aloud" as they constructed their formulas, and their responses were recorded on tape. The remaining three experts were given extensive, systematic guidance ("maximal guidance") in constructing their formulas that emphasized the use of analytical cognition (see Appendix A). These variations in the analysis-inducing conditions were implemented to encourage analysis and to obtain information about the engineers' analytical efforts, not to determine their differential effects on cognition. (They did not, in fact, result in significant differences in cognitive mode or in achievement among the engineers.) See Figure 4 for an illustration of mathematical formulas for aesthetics, safety, and capacity.

Insert Figure 4 about here

Independent Variables

The features that cause the depth and surface task conditions to differ in their propensity to induce intuitive or analytical cognition, as just described, can be measured with a task continuum index.

Task continuum index. Eight of the task characteristics predicted by cognitive continuum theory to induce different modes of cognition were used to construct a Task Continuum Index (TCI). The TCI includes measures of (a) the number of cues presented, (b) the redundancy among the cues (the mean intercorrelation), (c) the reliability of cue measurement (assigned a value of 1 in the bar graph and formula conditions, and estimated by the mean intercorrelation among the cue judgments of several experts for the film-strip condition), (d) the degree to which the task is decomposed for the subject, (e) the availability of an organizing principle to the subject, (f) the degree of nonlinearity in the optimal organizing principle (see explanation of second subindex of CCI, below), (g) the extent to which the cues are weighted equally in the optimal organizing principle for the task (standard deviation of the Beta weights), and (h) the degree of certainty in the criterion (R^2 of environment model). Scores on the eight measures were aggregated by adding them. In the absence of any information about the relative power of task properties to induce cognitive properties, or the possible interactions between them, the additive function was chosen because it is the simplest and most robust under the circumstances.

The TCI thus provides a measure that permits each of the three tasks to be located on the task continuum for both surface and depth conditions. The TCI values for the nine conditions are shown in Table 1. The row and column means of Table 1 indicate that although equal distances were not established among the conditions employed, the appropriate order was achieved.

Insert Table 1 about here

Dependent Variables

The effects of the independent variables described above were examined with respect to (a) the location of each subjects' cognitive activity on the cognitive continuum, (b) each engineer's degree of empirical achievement in predicting each criterion accurately in the nine conditions.

Cognitive continuum index. Four of the characteristics of cognition (predicted by cognitive continuum theory to discriminate between intuitive and analytical cognition) were available in the present study and thus used to construct a cognitive continuum index (CCI). The four were measures of (a) cognitive control, (b) organizing principle, (c) error distribution, and (d) differential confidence.

Cognitive control is measured by R_s, the linear predictability of the engineer's judgments in the film strip and bar graph conditions. This was deemed an acceptable approximation to cognitive control due to the low nonlinear use of cues that was observed in the data. In the formula condition, cognitive control was measured by the correlation between the answers produced by the formula the engineer intended to present to the research team and the formula he actually presented (see Appendix B).

The extent to which the engineer's judgments are produced by a nonlinear organizing principle is a second subindex of the CCI. This is measured by the difference between the R^2 of a nonlinear model of the judgments (whose predictors include squared cue measures and selected interaction terms) and the R^2 of the linear model.

Error distribution is measured by the kurtosis of the distribution of errors, that is, differences between the engineer's judgments and the criterion, after the judgments have been rescaled onto the same range as the criterion. A positive kurtosis denotes the peaked distributions expected to occur with analysis, where the answers are usually very accurate yet occasionally highly inaccurate.

The final measure included in the CCI is the difference between the engineer's confidence in his method and his confidence in his answers. Since method confidence is expected to be high in analysis, and answer confidence to be high in intuition, the greater the difference between these measures the more analytic the cognitive activity was expected to be.

The CCI was calculated so that if in any task condition an engineer exhibited (a) high cognitive control, (b) a highly nonlinear organizing principle, (c) higher kurtosis (more peaked, higher tails) in his error distribution (thus indicating a greater number of nearly correct answers and a larger number of large errors), and (d) greater difference between method and answer confidence, then he would receive a high analytical score on the CCI. If the reverse conditions held, the subject would receive a low analytical (and thus high intuitive) score on the CCI. Each raw measure was rescaled within each engineer to a common scale and the sub-scores were combined by a simple additive (equal weights) procedure. Therefore each score was relative to each engineer's own performance, not to an absolute score.

Note that both the CCI and the TCI are compensatory; a low score on one sub-index may be compensated for by a high score on another sub-index. This form was chosen because it represents the intersubstitutability of cognitive activities, an essential part of the general theory of probabilistic functionalism put forward by Brunswik (1952, 1956) and Hammond (1966, 1982).

Achievement. The correlation (r_a) between an engineer's judgments over the set of highways and the appropriate criterion (described below) were measured in each task in each display mode, using the methods described in Appendix B.

Knowledge is measured in the intuitive and quasi-rational surface conditions by G (from the lens model equation; see Appendix B). In the analytical mode, the correlation between the criterion and the answers produced by the engineer's intended formula serves as a measure of knowledge, i.e., of what the engineer could have achieved if he had executed his knowledge with perfect cognitive control. The distinction between the degree of accuracy achieved with the intended formula and with the formula actually used is essential in any effort to compare the use of analytical cognition with the use of intuition. (See Hammond et al., 1975, for a detailed discussion of the distinction between consistency and cognitive control; see also the literature on the discrepency between "mental models" and task properties in Simon, 1979.)

Procedure

Task Materials

The same set of forty highway segments was used in all nine cells of the study.

Statistical properties of the intuition-inducing (aesthetics judgment) task. The aesthetics criterion was produced by a group of 91 citizens who judged the 40 highways. In order to vary methods, some of the citizens viewed the film strips, some viewed slides, and some viewed photo-copies of one or four frames from the film strip. The slides and film strips were rated, and the photo-copies were rated or rank-ordered. The 91 citizens' judgments were factor analyzed. Only one factor was identified; there was no evidence of method factors. The score for each highway on this factor served as the criterion measure of its aesthetic value.

Eight aesthetics cues were presented to the engineers in the bar graph and formula tasks. The cue values were determined by averaged ratings of the cue values from 14 of the citizens, who rated the cues for each of the 40 highways upon viewing the film strips.

A linear model of the task yielded an R_e^2 of .937 (corrected for estimated shrinkage, .920). The correlation between each cue and the criterion, as well as the intercorrelations among the cues, is given in Table 2. The average intercorrelation among cues is .56.

Insert Table 2 about here

Statistical properties of the quasi rationality-inducing (safety judgment) task. The criterion for the accuracy of judgments is the accident rate, averaged over seven years, for each of the 40 highways. Accident rate is defined as the total number of accidents (involving fatalities, injuries, or only property damage) divided by the number of vehicle miles traveled. (One highway with an extremely high accident rate was considered to be an unrepresentative outlier and was not used in the analysis of safety judgments.)

Highways were measured on ten dimensions, chosen for inclusion in the study on the basis of discussions with highway safety experts who indicated the information they considered essential for evaluating the safety of a road (see Table 3 for list). Eight of these measures were available from highway department records; two measures (number of curves per mile and number of obstacles per mile) had to be counted by the experimenters from visual inspection of film strips of each highway segment. The beta weights for each dimension or cue in predicting accident rate are also presented in Table 3. Visual examination of the scatter-plots of the relations between each cue and the criterion indicated little if any nonlinear co-variation. This finding was supported by the results from calculation of the contribution of squared terms and interactions to accident rates, which is negligable.

Insert Table 3 About Here

An optimally weighted linear multiple regression model of the task indicates that R_e = .363; corrected for estimated shrinkage, R_e = .809. Application of equal weights and linear functions, each cue given the sign that appeared in the best fit equation, yields an R_e of .769 (corrected for shrinkage R_e = .667). The intercorrelations among the ten cues and the criterion are presented in Table 3.

Statistical properties of the analysis-inducing (capacity judgment) task. The criterion for the accuracy of judgments of capacity is the maximum number of vehicles that the road could carry in both directions in one hour under ideal conditions. Each highway's capacity was determined by applying a standard procedure from the Highway Capacity Manual (Highway Research Board, 1965) to the measured features of the highway (see Appendix C).

The highways were measured on nine dimensions, each of which was chosen for inclusion either because it was involved in the formal procedure that highway departments typically use for determining capacity or because it was plausibly related to capacity (see Table 4 for list). These measures were available from the Colorado Department of Highways records.

Insert Table 4 About Here

Because the capacity criterion is a fully determined function of the set of highway dimensions, the procedure also serves as the model of the environment. Thus, there is no environmental error, and the model of the environment is neither linear nor additive. The formulas in Appendix B show the approximate degree of nonlinearity in the model. Additionally, the

function forms have steplike discontinuities rather than being linear or smooth because the procedure involves tables. The model of the subject, on the other hand, is estimated by linear regression. And since the models of environment and subject are of different kinds, the generalization of the Lens Model Equation described by Stewart (1976) was used for this situation (see Appendix B for further detail).

Rating Scales

Rating scales were constructed to be appropriate to the cognitive activity induced. Thus, an abstract rating scale from 1 (low) to 10 (high) was used for judging aesthetics, safety, or capacity from the film strips, to induce intuitive cognition. In the bar-graph presentation and in the task requiring the construction of a formula, scales specific to the task were used because this specificity is compatible with calculation and thus with analytical cognition. Thus in the capacity judgment task a scale from 750 to 2500 vehicles per hour was employed, and in the safety judgment task a scale from 0 to 32 accidents per million vehicles miles traveled was employed. The 1 to 10 scale was used in all three surface task conditions for the aesthetics judgment task. Transformations to a common scale were made for purposes of data analysis.

Order of Presentation

All engineers were presented with the surface task conditions in the same order: first, the film strips; second, the bar graphs; third, the materials for formula construction. Surface conditions were deliberately not counterbalanced because it has already been demonstrated that analytical work requiring use of certain cues in an explicit fashion influences subsequent intuitive judgments, whereas the reverse is not true (Jones & Harris, 1982).

The order of depth conditions within each surface condition was counterbalanced across all engineers. Participation in each surface condition was separated by at least a week.

In the intuition-inducing surface condition, ten of the forty highways were shown twice; in the quasi rationality inducing surface condition sixteen highways were shown twice. These repetitions permitted calculation of repeated trials reliability for each engineer. These data were not used for comparison, however, because the values for the intuition-inducing conditions were inflated due to recognition of the highways in the film strips.

Time

Response times in the nine conditions were determined by surface task conditions and thus are not dependent variables; that is, presentation of a film strip necessarily required more of a subject's time than presentation of a bar graph. The mean response time in the film-strip condition (where the engineer saw approximately 100 separate exposures for each of 40 highway segments) was 64 seconds, and in the bar-graph condition (where the engineer was shown one bar graph for each highway segment), it was 19 seconds.

In the formula-producing condition the response time varied within the three subgroups. The 18 engineers in the "think aloud" and "minimal guidance" subgroups were encouraged to complete their formulas within forty-five minutes; but their mean time over all three tasks was 51 minutes. No time constraints were imposed on the engineers in the "maximal guidance" condition; mean response time over all three tasks was 2 hours and 40 minutes.

Hypotheses and Results

Two methods were used for analyzing the data; correlational analysis and order table analysis.

The correlational analysis examines the covariation between the TCI (task properties combined into an index of task location) and the CCI (cognitive properties combined into an index of cognitive location). Correlations computed for each engineer over the nine conditions indicate the extent to which (a) task location induces cognition to be activated at the predicted location, (b) task location is related to achievement, and (c) the absolute difference between the induced location of the engineer's cognitive activity (CCI) and the location of the task (TCI) is related to achievement.

The order table analysis allows us to ascertain whether task properties induce the predicted mode of cognition for each engineer for each of the surface and depth task conditions separately. The relation between the predicted and the observed order of location on the cognitive continuum among the three cells of a particular row (depth task condition) or column (surface task condition) of the study design (Figure 1) is examined by counting how many engineers had the expected order of location, measured in terms of the CCI. This method allows hypotheses to be tested by determining whether the number of engineers with the expected orders exceeds chance. A similar analysis is applied to the question of whether the correspondence of task location and cognitive location on their respective continua determine the degree of achievement in the nine task conditions examined.

The order table analysis thus provides a highly detailed description of each engineer's performance; it indicates why the correlations between TCI and CCI were as high or low as they were found to be.

Inducement

The inducement analyses are concerned with the extent to which the position of the task on the TCI induces cognition to be activated at a corresponding position on the CCI.

Correlational Analysis

H1: Task properties induce corresponding cognitive properties.

The Cognitive Continuum Index (CCI) was correlated with the Task Continuum Index (TCI) over the nine conditions for each engineer. These correlations were positive for 19 of the 21 engineers. Nine of the positive relations were significant at the $p < .05$ ($df = 7$, one-tailed) level. The mean correlation (after appropriate z-transformations) is .506 which is significantly different from zero ($t = 6.63$, $p < .001$, $df = 20$).

In addition, the CCI for each engineer was separately correlated with measures of depth task characteristics and surface task characteristics (the average value of each row and column in Table 1, respectively). The correlation between CCI and the surface TCI was positive for 18 engineers, and 6 of these relations were significant at $p < .05$ ($df = 7$, one-tailed). The mean correlation (appropriately z-transformed) was .384 ($t = 3.89$, $p < .001$, $df = 20$, one-tailed). Similarly, the correlation between CCI and the depth TCI was positive for 20 engineers (5 significant), and the mean correlation was .391 ($t = 5.36$, $p < .001$).

Regression of CCI onto surface and depth TCI provides evidence that surface task characteristics are more powerful than depth characteristics in inducing cognitive mode. Since the surface and depth TCI indices are derived from the same measure, their regression coefficients may be meaningfully compared. The mean b-coefficient for the surface TCI index was .599 ($t = 4.57$, $p < .001$, $df = 20$, one-tailed), and the mean depth TCI b-coefficient was .244 ($t = 6.60$, $p < .001$). The different size of the regression coefficients reflects the fact that although there was less range of variation on the TCI due to the surface conditions than to the depth conditions, nevertheless surface conditions were found to have as large an effect as depth conditions.

In sum, the results of the correlational analysis indicate that (a) task properties induce cognitive activity to assume corresponding properties, and (b) surface task conditions have a greater effect on inducement than depth task conditions.

> H2: When surface and depth task characteristics are congruent (i.e., occupy the same location on the task continuum), task characteristics will be most effective at inducing the corresponding mode.

When surface and depth task characteristics are congruent they should be most effective in inducing the corresponding mode of cognition. Hence, surface and depth task conditions should combine <u>additively</u> in inducing cognitive mode. Non-additive combination (e.g., conjunctive or disjunctive combination) would indicate that the additive model is not the best descriptor of how surface and depth task conditions combine in inducing location on the cognitive mode. For example, a conjunctive model would apply if analysis-inducing levels on <u>all</u>

task features (both surface and depth) are necessary to induce analytic cognition. On the other hand, a disjunctive model would apply if an analysis-inducing level on any task feature (either surface or depth) were sufficient to induce analytic cognition. To test these possibilities, conjunctive and disjunctive models as proposed by Einhorn (1971) were constructed for predicting CCI from depth and surface TCI, and their explanatory power (R^2) was compared with that of the simple linear additive model. The mean R^2's across the 21 engineers (arcsine transformed) were: linear, .456; conjunctive, .471; disjunctive, .470. The differences are negligable. Since the nonadditive competing models offer no significant advantage over the more parsimonious, additive, congruent model, the latter is accepted.

<u>Order table analyses</u>. The order table analysis tests the following hypotheses.

H3: Location on the cognitive continuum is induced by <u>surface</u> task characteristics, irrespective of depth task characteristics.

The results support the hypothesis. Table 5 shows that in the aesthetic judgment task, the three surface task conditions induced cognition to be activated in exactly the predicted order on the cognitive continuum (formula (A) > bar graph (Q) > film strip (I)) for eight engineers ($X^2 = 5.5$, $p < .02$). An additional nine engineers had two of the three predicted orders (A > Q, Q > I, and A > I). Three engineers had two departures from the expected order, and one engineer had three (i.e., a complete reversal of the predicted order). Thus, 17 of the 21 engineers were more consistent with the prediction than chance; that is, 17 had at least two of the three predicted pairwise relationships ($X^2 = 6.86$, $p < .01$). The pattern of results for the safety and

capacity tasks is similar. The same result appears when each engineer's CCI scores are averaged across the three depth tasks (right hand column of Table 5).

Insert Table 5 About Here

H4: Location of cognitive activity on the cognitive continuum is induced by depth task characteristics, irrespective of surface task characteristics.

The results support the hypothesis (see Table 6). In the film strip surface task condition (left column of Table 6), the three depth task conditions induced eight engineers' cognition to be activated on the cognitive continuum in exactly the predicted order (capacity (C) > safety (S) > aesthetics (E)) ($p < .02$), six engineers to have one deviation, five engineers to have two deviations, and one engineer to have three deviations (i.e., a complete reversal of the expected order). Within the bar graph condition, the number of engineers having the expected order or at least two of the three relationships was significant. Within the formula condition (Column 3), and when the engineers' CCI was averaged across all three surface task conditions (Column 4), there was a greater than expected number of engineers who had exactly the predicted order, although this number was not statistically significant. However, for each of these columns 18 engineers had at least two of the three predicted relations ($X^2 = 11.25$, $p < .001$). Thus, although depth task conditions (Table 6) induced the expected locations of cognitive activity on the cognitive continuum, they were not as effective as surface task conditions (Table 5).

Insert Table 6 About Here

Summary

Correlational analysis showed that the location of the task on the task continuum has the expected effect on the location of the engineer's cognitive activity on the cognitive continuum. Regression analysis supported the hypothesis that congruence between depth and surface task characteristics most strongly induces the corresponding cognitive mode. Order table analysis supported the correlational analysis and showed, in more detail, the significant effects of depth and surface task conditions on the location of the engineers' cognitive activity on the cognitive continuum.

The effects of surface and depth task characteristics, over the ranges manipulated in this study, are of approximately the same magnitude, although evidence from order table analysis and regression analysis indicates that surface task characteristics may be more powerful than depth in inducing cognitive activity to conform to expectations. The regression coefficients for the surface task variation were larger, indicating that variation in surface task characteristics as measured by TCI has a larger effect on the cognitive mode than variation in depth task characteristics.

Performance

Analysis as ceiling. Having demonstrated that task properties induce corresponding cognitive properties, we can now turn to the question of whether analytical cognition is, in practice, always superior to intuitive and quasi-rational cognition. In broad terms, the answer is clearly no. When judging capacity, 11 of the 20 engineers had higher achievement in the intuitive (film-strip) or quasi-rational (bar-graph) condition than in the

analytical (formula-producing) condition (Table 7-A). The same was true for 11 of the 21 engineers when judging safety (Table 7-B), and for 3 of the 21 engineers when judging aesthetics (Table 7-C). Clearly, analytical cognition did not, in practice, provide a ceiling which could not be exceeded by intuitive or quasi-rational cognition. Before proceeding to a statistical examination of these results we describe the role of extreme errors produced by analytical cognition.

The Extreme Errors of Analytical Cognition

One reason that analytical cognition fails to surpass quasi-rational and intuitive cognition consistently is that, as predicted, more extreme errors are made by this form of cognition. As Figure 5 illustrates, in the analytical (formula) surface condition, the range of achievement scores increases dramatically from aesthetics to safety to capacity. Thus the worst as well as the best performances are produced by analytical condition.

Insert Figure 5 about here

Detailed analysis of each engineer's performance shows how such errors come about. Engineer #2, for example, made a careless arithmetic error in producing the weights in his safety formula. He first assigned a weight of .10 to each of the ten cues. Next he adjusted the weights of important cues to .12. Finally, intending to assign weights of .08 to cues he felt were slightly less important, he wrote instead .8. Thus he gave the greatest weight to the cues to which he wished to give least weight. The effects of his error were serious: his achievement (r_a) was only .071, and his mean error was 44.2 on a scale he intended to run from 0 to 32. Similarly, on the capacity task, Engineer #8 intended to subtract a set of factors from the maximum capacity, 2500, but used an extra minus sign, so his formula produced

answers that correlated negatively with the capacity criterion (-.574). Correcting this error and another minor one produced a formula that performed at .879, moving him from being the worst performing engineer to the best performing engineer on this task. Errors of this type, capable of affecting the engineer's entire performance, appeared more often in the formula condition than in the filmstrip or bar graph conditions.

Further, among the three formula conditions, the errors became more serious as the depth task condition became more analytical (as TCI increased). The seriousness of an error can be evaluated by the correlations of the answers produced by the erroneous formula with the answers produced by a corrected formula. Among the eight engineers with erroneous aesthetics formulas, the median correlation between corrected and uncorrected formulas is .997, indicating that the errors in this intuition-inducing depth task were not at all serious. The median correlation between corrected and uncorrected formulas for the seven engineers who made errors on their safety formulas is .715, and the median for the nine engineers with capacity formula errors is .668. Thus, the most serious errors in the formula condition were produced in the most analysis-inducing depth task, capacity judgment.

But the extreme errors of analytical cognition are not the only reason why it is frequently outperformed by the engineers' intuitive and quasi-rational cognition. Removing the effects of errors by using the measure G from the Lens Model Equation (see Appendix B) shows that performance in the analytical surface task is exceeded by performance in the intuitive or quasi-rational condition for 12 of the 20 engineers on the capacity task, for 12 of the 21 engineers on the safety task, and for 14 of the 21 engineers on the aesthetics task. Therefore, in practice, analytical cognition does not represent an upper bound for performance, even when the occasional large

errors in its execution have been corrected.

The fragility of analysis, illustrated by the appearance of large errors in the analytical but not the intuitive or quasi-rational surface condition, was first emphasized by Brunswik (1956, p. 92), who contrasted the dangers from the errors of perception with the errors of analyses in this way:

> the "stupidity" of perception thus is by no means to be construed to mean maladaptiveness; as we all know, life has survived on relative stupidity from time immemorial, and if threatened in its existence it is so by malfunctioning of the intellect rather than by malfunctioning of perception.

<u>Hypotheses Regarding TC, CCI, and Performance</u>

The principal hypotheses are that performance will be best (a) when the surface task characteristics are <u>congruent with</u> the depth task characteristics and (b) when the engineer's cognitive mode <u>corresponds to</u> the task characteristics.

<u>Correlational Analyses</u>

The hypotheses concerning the effects of congruence and correspondence on performance may be investigated by correlating performance measures with measures of surface and depth task (TCI) and of location of cognitive activity (CCI), as well as with indices of congruence between surface and depth task and of correspondence between TCI and CCI. Performance is measured by achievement (r_a).

Surface-depth Congruence and Performance

The hypothesis that congruence between surface and depth task characteristics determines performance may be tested by creating a variable in which a "2" is assigned to the cells on the descending diagonal (in Figure 1), a "1" to the adjacent cells, and a "0" to the corner cells. This variable is orthogonal to surface and depth task conditions.

H5: The greater the congruence between surface and depth task characteristics, the higher the engineer's achievement.

The mean of the z-transformations of the correlations between r_a and the measure of congruence is −.181 with a standard error of $\pm$.063 (corresponding to a correlation of −.179), which is significally different from zero ($p < .01$, $df = 20$, two-tailed). These results suggest that congruence between surface and depth is only slightly associated with higher achievement. The order table analysis (below) indicates the reason for this result.

Mode-task Correspondence and Performance

The hypothesis that the correspondence of the engineer's cognitive mode to the task determines performance may be investigated by measuring the absolute difference between the location of each engineer's cognitive activity on the cognitive continuum and the task location on the task continuum $|TCI - CCI|$.

H6: The greater $|TCI - CCI|$, the lower the engineer's achievement (r_a).

The mean z-transformed correlation between |TCI - CCI| and r_a is -.370 $\pm$.067, significantly different from zero ($p < .001$, df = 20, two-tailed). Thus, the results indicate that performance is better when the engineer's cognitive mode corresponds to the task's location on the cognitive continuum.

Both sets of results support the importance of task conditions: the first indicates that performance is better when surface and depth aspects of task are congruent. The second indicates that performance is better when cognitive mode corresponds to task. These results contradict the conventional view that analytical cognition always leads to higher performance.

<u>Order Table Analysis</u>

The hypotheses concerning the effects of surface/depth congruence and mode/task correspondence on performance were also investigated with the order table method.

<u>Surface/Depth Congruence</u>

Whereas the correlational analysis of the surface/depth congruence hypothesis investigated the relationship between performance and a measure of surface/depth congruence over all nine cells of the study design (Figure 1), the order table analysis investigates the relationship within each row, that is, for each depth task. The order table analysis allows us to pinpoint conditions that agree or disagree with the hypothesis because it provides a more detailed investigation of the relationship.

H7: Achievement (r_a) should be best when the surface and depth task conditions are congruent. That is, they should be in the order I > Q > A, (e.g., r_a greater in film strip than bar graph than formula) for the intuition-inducing aesthetics judgment task,

in the order A > Q > I (i.e., formula > bar graph > film strip) for the analysis-inducing capacity judgment task, and in the order Q > I > A or Q > A > I for the quasi rationality inducing safety judgment task.

The results regarding achievement clearly disconfirm Hypothesis 7. The fir. columns of Tables 7A, 7B, and 7C show that although the predicted results were found in the analysis-inducing depth conditions (capacity), the opposite results were found in the intuition-inducing depth conditions (aesthetics) and no significant results were found in the quasi rationality inducing depth conditions (safety).

Insert Table 7 about here

A competing hypothesis is the conventional one:

H8: Cognition in analysis-inducing surface task conditions is best for all engineers across all tasks.

The results regarding achievement support Hypothesis 8 (see column 1 of Tables 7A, 7B and 7C); there is evidence for achievement being in the A > Q > I order in each of the depth conditions; this was especially true for aesthetics.

Mode/Task Correspondence

Whereas the correlational analysis of the mode/task correspondence hypothesis investigated the relationship between performance and a measure of the extent to which the engineer's location on the cognitive continuum was similar to the task's location on the task continuum, |TCI - CCI|, over all nine cells of the study design, the order table analysis indicates, for each

depth task condition, whether the engineer's performance is best when his cognitive mode, however induced, corresponds to the characteristics of that depth condition. For example, if on the capacity task the engineer's cognitive mode was more analytic in the bar graph condition than in the formula condition, then his performance should be better in the bar graph condition than in the formula condition because the capacity task is predicted to induce analysis. Specifically,

> H9: The order of magnitude of achievement (r_a) in the aesthetics task should be I' > Q' > A', in the safety task Q' > I' and Q' > A', and in the capacity task A' > Q' > I'.
>
> Here I' is the surface condition in which the engineer's cognition is most intuitive for a given depth condition, A' is the surface condition in which his cognition is most analytical, and Q' is the condition in between.

The results regarding achievement (third column of Table 7) are similar to those concerning the surface/depth congruence hypothesis. That is, in the capacity condition, seven of the engineers had the expected order A' > Q' > I', and ten had only one deviation from it. However, in the safety condition the number of engineers who had the expected order was not above chance, and, again, in the aesthetics condition the results were <u>opposite</u> from the prediction.

> H10: Achievement (r_a) is highest for all engineers across all tasks in the analytical (formula producing) conditions.

The results partially support this hypothesis; at least two of the three expected relations hold for 17 ($p < .01$), 12 (n.s.), and 15 ($p < .05$) engineers in the capacity, safety, and aesthetics conditions, respectively.

Engineers' successful prediction of the aesthetics criterion by construction of formulas. Eighteen of the 21 engineers were most accurate in predicting the aesthetic value of the highways by means of a formula (in contrast to visual inspection!). Moreover, judgments made by the engineers in all surface conditions of the aesthetics task were highly accurate (mean $r_a = .91$). Such high accuracy is rarely seen in studies of expert judgment, and such high accuracy in an aesthetics task by means of an equation was particularly surprising. And it is the high accuracy in this condition that produces the low correlations between mode/task correspondence and performance.

Consideration of this anomaly is instructive for several reasons. Examination of the nature of the criterion and the nature of the formulas produced would have made the result highly predictable, had this information been available prior to the collection of data because (a) the TCI value for the aesthetics task was 3.156, the lowest, as it should have been, for all tasks; (b) the criterion for aesthetics was developed from perceptual judgments of the highways from film strips and photographs by ninety-one citizens; (c) the cues were rather highly intercorrelated ($r = .556$); and (d) the linear predictability of the citizens' judgments was essentially perfect ($R^2 = .99$). These task properties imply that if the engineers were to produce linear, additive formulas (e.g., a weighted sum formula) such formulas would be highly accurate, even if their weights were far different from those used by the citizens. And that is what happened; 15 of the engineers did construct linear additive formulas (in contrast to 4 in both the safety task

and the capacity task), and the remaining formulas consisted of only minor deviations from this type.

Most important is the reason <u>why</u> the engineers used this type of equation; their explanations (taken from the "think-aloud" procedure and post-test interviews) indicate that the engineers had never attempted such a task before, that they had no conceptual means for coping with it, and, therefore, they could think of no solution other than to "add up the factors," and thus produce a weighted sum. Thus, they made <u>explicit</u> use of the same organizing principle <u>implicitly</u> used by the members of the citizens' panel (and themselves) when judging the highways by perceptual means.

Use of the same organizing principle would not, however, account for the <u>superior</u> performance of the formulas created by the engineers over the other two sets of judgments. Superior performance was achieved because the same organizing principle was applied inconsistently in the intuition-inducing and quasi-rationality-inducing surface conditions, but was applied with perfect consistency (and, as we showed above, with negligeable error) in the analysis-inducing, formula condition. The lens model equation (see Appendix B) provides a measure of performance (G) when the effects of inconsistency and error are removed. Column 2 of Table 7-C presents the order table analysis of G for aesthetics. While the order over the surface conditions is still in the reverse direction for the majority of engineers, the result is not statistically significant. This result suggests that the unexpectedly high achievement of the engineers' formulas can be explained by the fact that the organizing principle explicitly adopted by the engineers is identical with the intuitive organizing principle. This principle is applied consistently in the analytical surface condition. It is, however, applied inconsistently in the intuitive and quasi-rational surface conditions, and therefore performance in

the latter conditions is lower than that in the analytical condition.

Summary and Discussion of Performance Analyses

The correlational analysis shows that achievement is higher when surface task properties are congruent with depth task properties, and when location of the engineer's cognitive activity corresponds to the task's location on the task continuum. But the relationship was weak.

The order table analyses provided an explanation for the generally low correlations. Although the order of performance among the surface task conditions corresponded to the expected order for most engineers in the capacity depth task condition, the relation was weak in the safety depth task condition, and was reversed for most engineers in the aesthetics depth task condition. Therefore, it is the engineers' high achievement (mean $r_a = .91$) in the analytical formula-producing condition of the aesthetic task that is responsible for the weak relation between achievement and correspondence between TCI and CCI. Examination of the properties of the derivation of the criterion for the aesthetics task showed that it had linear, additive structure, which, together with the engineers unwitting but more consistent use of a similar organizing principle, accounted for the anomalous result.

Summary

We began this article by drawing a distinction between indirect and direct comparisons of intuitive and analtyical cognition. We indicated that indirect comparisons inform us about the proportion of persons in various populations whose intuitive and quasi-rational judgments fail to achieve the various standards or models of analytical cognition under various circumstances. Direct comparisons, on the other hand, inform us about the relative efficacy of intuitive, quasi-rational and analytical cognition (as

the latter is actually employed) compared to an empirical criterion (rather than a product of a logical model) under various conditions and within various populations. Although many indirect comparisons have been made (see especially Kahneman et al., 1982) we can find no previous direct comparisons.

Direct comparisons were made by ascertaining the relative efficacy of twenty-one expert highway engineers' use of intuition, quasi rationality and analysis. Each engineer was studied individually over nine conditions, each of which was located on a task continuum index (TCI) defined in terms of eight measures selected a priori. The subjects' cognitive activity in each of the nine conditions was located on a cognitive continuum index (CCI) defined in terms of the subjects' performance on four measures, also selected a priori. Both continua ran from intuition through quasi rationality to analysis.

The results of the direct comparison of intuitive, quasi-rational and analytical cognition described above indicate not only that intuitive and quasi-rational cognition <u>can</u> perform as well as human analytical cognition, but that superior performance can occur <u>frequently</u>: intuitive or quasi-rational cognition outperformed analytical cognition for roughly half the subjects on at least one occasion.

More specific predictions were made regarding the relations between the TCI and the CCI. The first prediction was that task properties would induce corresponding cognitive properties; that is, the location of each task condition on the TCI would induce each subject's cognitive activity to be activated at a corresponding position on the CCI. The results generally supported this prediction, which was a necessary precondition for the second prediction.

The second prediction was that the closer the correspondence between task location on the TCI and the subject's cognitive location on the CCI, the more accurate the expert's judgment would be. The results suggested a weak relationship that was unanticipated, but understandable given the nature of the aesthetics criterion and the additive formulas used by the engineers.

Thus, the relative efficacy of different modes of cognition--including analytical cognition--varies with task properties. Future research will need to focus on the specification of how task properties combine to induce cognition to change and how such changes affect performance.

These results have two types of implications, those concerned with the relative efficacy of different forms of cognition, and those concerned with the use of cognitive continuum theory. With regard to relative efficacy, the results imply that, in practice, the efficacy of analytical cognition does not invariably surpass the efficacy of intuitive or quasi-rational cognition, even when the decrement in performance caused by the large errors of analysis is eliminated. The relation between task properties and cognitive properties may be a better predictor of efficacy.

With regard to the use of cognitive continuum theory the results imply, first, that the general index of task location (or an improved version of it) can be used to describe any cognitive task. Thus, tasks used by various investigators can be directly compared to one another with regard to their location on the TCI. Identification of TCI locations of the various tasks used by researchers would thus show the complementarity of much of the current work in cognition that now mistakenly appears to be competitive. For example, discovery of the TCI for say, Anderson's (1981) work on children's perception of rectangularity and the TCI for Simon's work on the puzzle of the Tower of Hanoi and similar analysis-inducing problems (1979) would permit the

recognition of the complementarity of these endeavors.

Second, the general index of cognitive location (or an improved version of it) can be used to described cognition in *any* cognitive task. Use of this index together with the index of task location can lead to the achievement of *cumulative* results, a feature of research badly needed (see, for example, Meehl, 1978, who makes a strong plea for efforts to establish cumulative results). For example, if differential task location can show the work of Anderson and Simon to be complementary, then the description of the results of such work in the common terms of the index of cognitive activity would allow each set of results to be incorporated in a general theory and thus become *cumulative*.

In short, the two indices provide a means, and thus an opportunity, for *unifying* the work in cognitive psychology.

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Author Notes

This research was supported by the Engineering Psychology Programs, Office of Naval Research, Contract N00014-81-C-0591, Work Unit Number No. 197-073 and by BRSG Grant #RR07013-14 awarded by the Biomedical Research Support Program, Division of Research Resources, NIH. Center for Research on Judgment and Policy, Institute of Behavioral Science, University of Colorado.

Table 1

Task Continuum Index (TCI) Values for Each Cell of Study Design and for Each Depth Condition (Row Marginals) and Surface Condition (Column Marginals)

	Intuition	Quasi Rationality	Analysis	Depth Task Index (mean)
Aesthetics	1.844	3.531	4.094	3.156
Safety	5.377	6.904	7.466	6.582
Capacity	6.957	8.564	9.127	8.216
Surface Task Index (mean)	4.726	6.333	6.896	

Table 2

Aesthetics: Intercorrelations among Cues

	ATTR	RDCON	SCENE	CUL	LNDSCP	COLOR	VEG	TERRAIN
RDCON	.471							
SCENE	.830	.179						
CUL	-.187	.017	-.156					
LNDSCP	-.818	-.441	-.682	.134				
COLOR	.837	.222	.955	-.137	-.671			
VEG	.765	.186	.833	-.068	-.603	.875		
TERRAIN	.626	.061	.708	-.292	-.428	.704	.559	
AESTHETICS	.873	.224	.938	-.262	-.690	.929	.855	.735

ATTR, attractiveness of design
RDCON, road condition
SCENE, scenery
CUL, amount of roadside culture
LNDSCP, amount of reparative landscape
COLOR, color
VEG, vegetation
TERRAIN, type of terrain
AESTHETICS, aesthetics criterion

Table 3

Safety: Intercorrelations among Cues

	LWIDTH	SWIDTH	PCTNPZ	CURVEPM	GRADE	TRAFVOL	TRAFMIX	INTPM	AVESL	OBSPM
SWIDTH	.414									
PCTNPZ	-.046	-.251								
CURVEPM	.203	-.357	.554							
GRADE	-.294	-.254	.152	.360						
TRAFVOL	.492	.214	.135	.169	-.098					
TRAFMIX	-.229	.037	-.112	-.280	-.009	-.330				
INTPM	-.070	-.076	-.010	-.284	-.159	-.083	.032			
AVESL	.101	.457	-.481	-.591	-.265	-.106	.322	-.165		
OBSPM	.068	-.408	.647	.747	.291	.148	-.315	.079	-.674	
ACCRATE	-.083	-.466	.393	.558	.295	-.105	-.230	.304	-.717	.743

LWIDTH, lane width;
SWIDTH, shoulder width;
PCTNPZ, percent no passing zone;
CURVEPM, curves per mile;
GRADE, percent with substantial grade;
TRAFVOL, traffic volume;
TRAFMIX, traffic mix (percent trucks);
INTPM, intersections per mile;
AVESL, average speed limit;
OBSPM, obstacles per mile;
ACCRATE, total accident rate.

Table 4

Capacity: Intercorrelations among Cues

	LWIDTH	LATCLEAR	SIDEOBS	INTPM	TRAFMIX	TERRAIN	ASGRADE	LSGRADE	AVESL
LATCLEAR	.280								
SIDEOBS	-.286	-.860							
INTPM	-.083	-.129	.176						
TRAFMIX	-.228	.160	-.088	.039					
TERRAIN	.136	-.168	.161	-.380	-.082				
ASGRADE	-.234	-.242	.246	-.251	-.021	.354			
LSGRADE	-.141	.014	.146	-.196	-.071	.357	.794		
AVESL	.028	.246	-.247	-.143	.325	-.402	-.147	-.085	
CAPACITY	.587	.470	-.529	.074	-.424	-.433	-.615	-.535	.107

LWIDTH, lane width
LATCLEAR, lateral clearance
SIDEOBS, side obstacles
INTPM, intersections per mile
TRAFMIX, traffic mix (percent trucks)
TERRAIN, type of terrain
ASGRADE, angle of steepest grade
LSGRADE, length of steepest grade
AVESL, average speed limit
CAPACITY, DOH capacity criterion

Table 5

Effect of Surface Condition on Cognitive Continuum Index (CCI)*

		Depth Task Conditions						Cognitive Continuum Index Averaged Across All Depth Conditions for Each Engineer	
		Aesthetics		Safety		Capacity			
		Expected	Observed	Expected	Observed	Expected	Observed	Expected	Observed
Expected Order	A > Q > I	3.5	8	3.5	8	3.33	10	3.33	9
One departure from expected order	A > I > Q	3.5	8	3.5	5	3.33	4	3.33	6
	Q > A > I	3.5	1	3.5	5	3.33	3	3.33	1
Two departures from expected order	Q > I > A	3.5	1	3.5	0	3.33	1	3.33	2
	I > A > Q	3.5	2	3.5	0	3.33	1	3.33	1
Three departures from expected order	I > Q > A	3.5	1	3.5	3	3.33	1	3.33	1
Test of Expected Order		$X^2 = 5.49, p < .02$		$X^2 = 5.49, p < .02$		$X^2 = 13.71, p < .001$		$X^2 = 9.63, p < .01$	
Test of 0 or 1 Departures From Expected Order		$X^2 = 6.86, p < .01$		$X^2 = 9.33, p < .01$		$X^2 = 8.45, p < .01$		$X^2 = 6.05, p < .02$	

*Cell values are expected and observed numbers of engineers exhibiting each possible CCI order among the formula (A), bar graph (Q), and film strip (I) surface task conditions.

Table 6

Effect of Depth Condition on Cognitive Continuum Index (CCI) for Each Surface Condition*

		Surface Task Conditions						Cognitive Continuum Index Averaged Across All Surface Conditions for Each Engineer	
		Film Strip		Bar Graph		Formula			
		Expected	Observed	Expected	Observed	Expected	Observed	Expected	Observed
Expected Order	C > S > E	3.33	8	3.33	9	3.33	6	3.33	5
One departure from expected order	C > E > S	3.33	3	3.33	0	3.33	3	3.33	2
	S > C > E	3.33	3	3.33	6	3.33	9	3.33	11
Two departures from expected order	S > E > C	3.33	3	3.33	3	3.33	1	3.33	1
	E > C > S	3.33	2	3.33	1	3.33	0	3.33	0
Three departures from expected order	E > S > C	3.33	1	3.33	1	3.33	1	3.33	1
Test of Expected Order		$x^2 = 6.25, p < .02$		$x^2 = 9.63, p < .01$		$x^2 = 1.70$, n.s.		$x^2 = 0.49$, n.s.	
Test of 0 or 1 Departures From Expected Order		$x^2 = 2.45$, n.s.		$x^2 = 4.05, p < .05$		$x^2 = 11.25, p < .001$		$x^2 = 11.25, p < .001$	

*Cell values are expected and observed numbers of engineers exhibiting each possible CCI order among the capacity (C), Safety (S) and Aesthetics (E) depth task conditions.

Table 7

Effect of (a) Surface-Depth Congruence and (b) Mode-Task Correspondence on Performance as Measured by Achievement (r_a) and Knowledge (G)

		7-A CAPACITY				
		Surface-Depth Congruence Hypothesis		Mode-Task Correspondence Hypothesis		
		r_a	G	r_a	G	
3 Expected Relations	A > Q > I	9	7	7	4	For Hypothesis
2 of 3 Expected Relations	A > I > Q	0	1	5	6	For Hypothesis
	Q > A > I	8	9	5	5	For Hypothesis
1 of 3 Expected Relations	Q > I > A	3	2	2	2	Against Hypothesis
	I > A > Q	0	0	1	1	Against Hypothesis
0 of 3 Expected Relations	I > Q > A	0	1	0	2	Against Hypothesis
Test of Expected Order		$x^2 = 9.63$, $p < .01$	$x^2 = 3.62$, $p < .10$	$x^2 = 3.62$, $p < .10$	$x^2 = .010$, NS	
Test of 0 or 1 Departures from Expected Order		$x^2 = 8.45$, $p < .01$	$x^2 = 8.45$, $p < .01$	$x^2 = 8.45$, $p < .01$	$x^2 = 4.05$, $p < .05$	

		7-B SAFETY				
		Surface-Depth Congruence Hypothesis		Mode-Task Correspondence Hypothesis		
		r_a	G	r_a	G	
Both Expected Relations	Ω > A > I	2	0	4	5	For Hypothesis
	Ω > I > A	6	6	6	3	
One Expected Relation	I > Ω > A	2	8	2	5	Neutral
	A > Ω > I	9	0	2	1	
Neither Expected Relation	A > I > Ω	0	0	6	1	Against Hypothesis
	I > A > Ω	2	7	1	6	
Test of Expected Order		$x^2 = .054$ NS	$x^2 = .054$ NS	$x^2 = 1.34$ NS	$x^2 = .054$ NS	

		7-C AESTHETICS				
		Surface-Depth Congruence Hypothesis		Mode-Task Correspondence Hypothesis		
		r_a	G	r_a	G	
3 Expected Relations	I > Q > A	0	2	1	6	For Hypothesis
2 of 3 Expected Relations	I > A > Q	0	2	3	3	
	Q > I > A	1	3	2	2	
1 of 3 Expected Relations	Q > A > I	2	7	2	5	Against Hypothesis
	A > I > Q	4	2	7	2	
0 of 3 Expected Relations	A > Q > I	14	5	6	3	
Test of Expected Order		$X^2 = 3.09$ (reversed direction) $p < .10$	$X^2 = .34$ (reversed direction) NS	$X^2 = 1.37$ (reversed direction) NS	$X^2 = 1.37$ (expected direction) NS	
Test of 0 or 1 Departures from Expected Order		$X^2 = 15.43$ (reversed direction) $p < .001$	$X^2 = 1.71$ (reversed direction) NS	$X^2 = 3.05$ (reversed direction) $p < .10$	$X^2 = 0.0$ NS	

Figure Captions

Figure 1. Design of the study.

Figure 2. Frame from film strip of a two-lane rural Colorado highway.

Figure 3. Bar graph presenting safety-relevant information about a highway.

Figure 4. Example formulas for aesthetics, safety, and capacity.

Figure 5. Medians and ranges of achievement in each condition.

		SURFACE TASK CHARACTERISTICS		
		Film Strips (Intuition Inducing) I	Bar Graphs (Quasi Rationality Inducing) Q	Formulas (Analysis Inducing) A
DEPTH TASK CHARACTERISTICS	Aesthetics (Intuition Inducing) E	EI	EQ	EA
	Safety (Quasi Rationality Inducing) S	SI	SQ	SA
	Capacity (Analysis Inducing) C	CI	CQ	CA

HIGHWAY JUDGMENT PROJECT 1982

BAR GRAPH PRESENTATION. CAPACITY JUDGMENT TASK.

```
                              8             10                   13
Lane Width                    XXXXXXXXXXXXXXX

                              0         2                        >6
Lateral Clearance             XXXXXXXXXXX

                              0                                   2
Obstructions                  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

                              0                                   4
Intersections per Mile        XX XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

                              0                       24         35
Traffic Mix                   XXXXXXXXXXXXXXXXXXXXXXXXXX

                              1                                   3
Terrain                       XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

                              <3         3.6                      7
Angle of Steepest Grade       XXXXXXXXXXXXX

                              0           .17                    .5
Length of Steepest Grade      XXXXXXXXXXXXXX

                              30                45               60
Average Speed Limit           XXXXXXXXXXXXXXXXXXX
```

AESTHETICS FORMULA:

$$\text{AESTHETICS VALUE} = \frac{3}{16} * \text{ATTR} + \frac{3}{16} * \text{RDCON} + \frac{9}{64} * \text{SCENE}$$

$$- \frac{3}{16} * \text{CUL} + \frac{9}{32} * \text{LNDSCP} + \frac{9}{56} * \text{COLOR}$$

$$+ \frac{9}{56} * \text{VEG} + \frac{9}{16} * \text{TERRAIN} - \frac{149}{112}$$

SAFETY FORMULA:

$$\text{ACCIDENT RATE} = \frac{12.8 * (23 - (\text{SWIDTH} + \text{LWIDTH}))}{15}$$

$$+ \frac{12.8 * (\text{OBSPM} + \text{CURVEPM} + \text{INTPM})}{29}$$

$$+ \frac{6.4 * (\text{TRAFMIX} + \text{PCTNPZ})}{115}$$

CAPACITY FORMULA:

$$\text{CAPACITY} = 2 * (\text{LWIDTH} - 8) - .25 * \text{TRAFMIX}$$

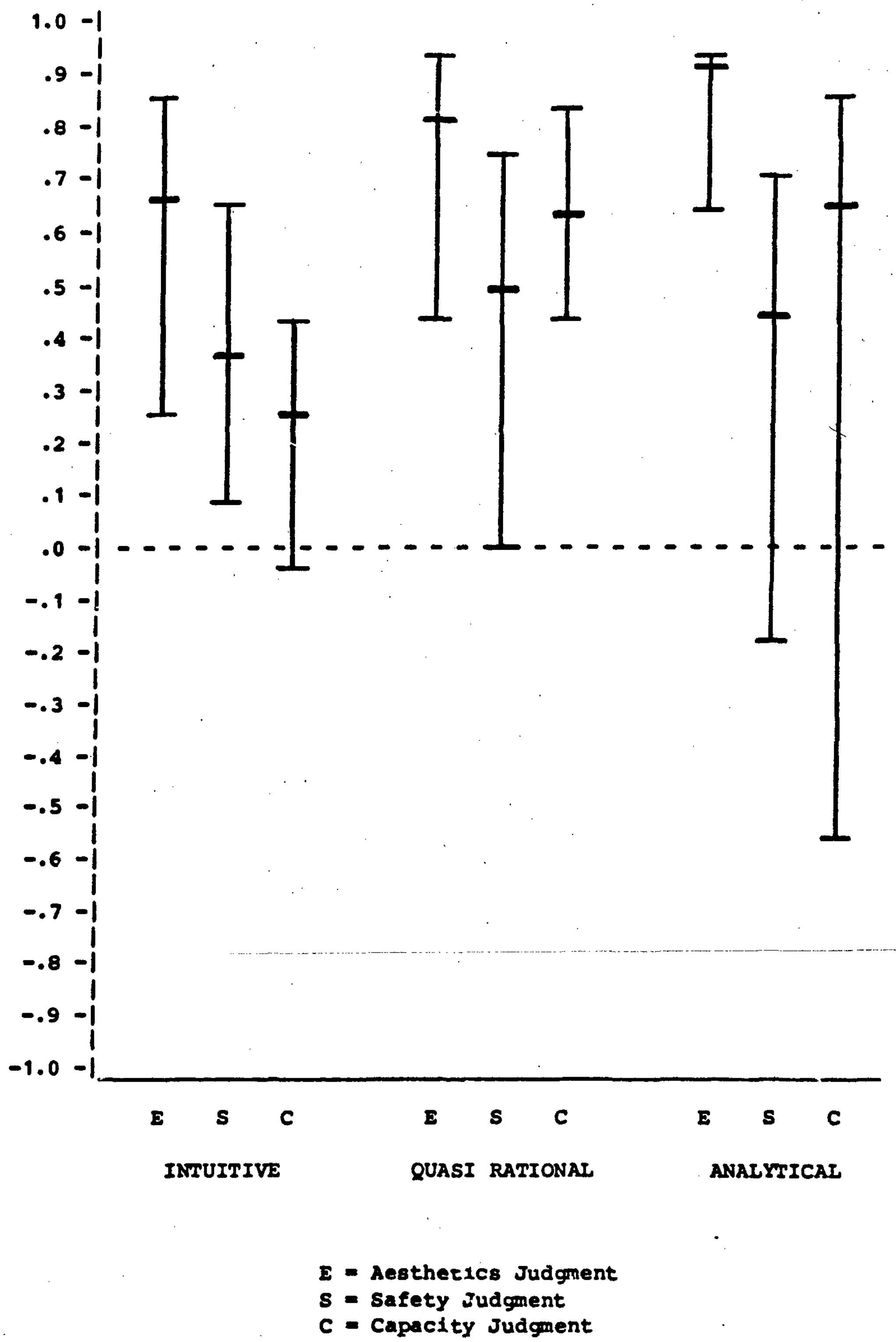
$$- 2 * \text{INTPM} - .25 * (\text{AVESL} - 30)$$

$$- 1.5 * (\text{ASGRADE} - 3) - 3 * \text{LSGRADE}$$

$$+ .5 * \text{SIDEOBS} * (\text{LATCLEAR} - 6)$$

$$+ .33 * \text{TERRAIN}$$

Note: Variables for aesthetics, safety and capacity formulas are defined in Tables 2, 3, and 4 respectively.


1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
E S C
INTUITIVE
E S C
QUASI RATIONAL
E S C
ANALYTICAL
E = Aesthetics Judgment
S = Safety Judgment
C = Capacity Judgment

APPENDIX A

Maximal Guidance Procedure

This procedure was designed to give the engineer a maximum of guidance in constructing his formula for safety in order to prevent the commission of minor errors and to ensure that his formula adhered to principles of measurement theory with which he might not be familiar. The procedure consisted of the following steps:

-- Specify the answer scale.

-- Specify the scale for each input dimension and its overall relation to the answer scale, and identify possible interactions with other dimensions.

-- Group the input dimensions according to their redundancy, similarity, or mutual interactions.

-- Express the formula as a hierarchy of groups of variables.

-- Determine what organizing principle should be used at each level of hierarchy.

-- Specify the function form governing each dimension's input to its organizing principle.

-- Combine all the above information into one formula.

The engineer was guided through these steps by a series of forms which contained instructions for the steps and choice points, and on which intermediate steps were recorded. Two examples follow. The engineer also received detailed tutorials about interactions and organizing principles as part of the maximal guidance procedure.

Form 1: Answer Dimension Form

Name ____________________ Task ____________________

Answer dimension's units ___________________.

Range of possible answers: Low _______ High _______.

A "natural 0" on a scale means that when it is called "0" there really is NONE of the quality being measured. If you had a natural 0, then it would make sense to say that an "8" is twice as much of a thing as a "4"; but if the 0 was arbitrary, it wouldn't have that sort of meaning.

For example, if you have savings of $10,000, you have twice as much money as if you had $5000, because 10000 is twice 5000. Here the $0 is a natural 0. But 32 degrees F is not twice as warm as 16 degrees F, because the 0 on the temperature scale is picked arbitrarily. In other words, it does not have a natural 0.

Does the answer dimension have a natural 0? Yes _____ No _____.

It is useful, when considering numbers that measure a dimension, to ask whether the intervals between the numbers have consistent meaning, or whether the numbers simply express order. For example, is the difference between a 1 and a 2 the same as the difference between an 11 and a 12? In the above measures of money or temperature, the intervals do have consistent meaning. However if we were to assign numbers to grades on a test, where A = 1, B = 2, C = 3, D = 4, E = 5, and F = 6, the interval between 2 and 4 would be different in meaning from the interval between 4 and 6. All the numbers convey is that A is better than B, etc.

Do the intervals in the answer scale have a consistent meaning?
Yes _____ No _____.

Form 3: Choice of Organizing Principle

This form is for use in deciding what organizing principle to use for producing either the final answer or an intermediate product to be plugged in at a higher level in the hierarchy.

__Output__.

Is this the top level, producing the final answer? Yes ____ No ____.

If so, what are the units of the final answer? _______________.

What is its range? Low _____ High _____.

If this is not the top level, then the output of this organizing principle will be input for an organizing principle at a higher level.

What organizing principle is used at the next higher level? ____________.

What kind of input does it require? Units __________.

Range: Lowest point _______, Highest point _______;

Does it need to have a natural 0? _______.

__Input__.

List the input dimensions:

__Organizing Principle__.

What organizing principle do you want to use here? (Refer to Sheet 2 for guidance in your choice, and to the Forms 2-i and 2-g that you used to describe these dimensions to see what kinds of interaction they have with each other.)

Check one: Averaging ___. Multiplying ___. Table (Configural) ___.
Other ___.

APPENDIX B

Derivation of Measures of Achievement, Knowledge, and Cognitive Control from the Lens Model

The Lens Model

Achievement can be decomposed into several components by means of the Lens Model Equation (Hammond, et al., 1975) as follows:

$$r_a = G\,R_e\,R_s + C\sqrt{1 - R_e^2}\,\sqrt{1 - R_s^2}$$

where

r_a = achievement, the correlation between the engineer's judgments and criterion values

G = the correlation between judgments and criterion values corrected for attenuation due to less than perfect linear predictability in each

R_e = predictability (linear form) of criterion from cues

R_s = predictability (linear form) of subject's judgments from cues

C = correlation between residuals from linear predictions of criterion and residuals from linear predictions of subject's judgments.

The Lens Model for capacity judgments is a variant of this.

Capacity

In the capacity judgment task, the environmental model, derived from the Highway Capacity Manual (Highway Research Board, 1965), involves nonlinear cue use, while the engineer's judgments are fit with a linear model. Since the models are different, it cannot be assumed that the residuals of one model are uncorrelated with the predictions of the other. There must now be four terms in the lens model equation (Stewart, 1976, pp 114, 115). Thus:

$$r_a = G\, R_e\, R_s + r(\hat{Y}_e, Z_s)\, R_e \sqrt{(1-R_s^2)} + r(Z_e, \hat{Y}_s)\sqrt{(1-R_e^2)}\, R_s + C\sqrt{(1-R_e^2)}\sqrt{(1-R_s^2)}$$

However, since environmental prediction is perfect (due to the fact that the capacity criterion was produced by the environmental model, from the cue values), $R_e = 1$ and $\sqrt{(1-R_e^2)} = 0$, so two terms drop out of this equation, leaving the formula

$$r_a = G\, R_e\, R_s + r(\hat{Y}_e, Z_s)\, R_e \sqrt{(1-R_s^2)}$$

Most previous work with the Lens Model (and judgment research in general) has involved linear models of the environment. Therefore it is of interest to see how closely the nonlinear criterion can be predicted by a linear model involving the cues that were available to the engineer--the 7 cues used in creating the criterion as well as the measures of (a) intersections per mile and (b) average speed limit, which were made available to the engineer during his judgments in all three modes.

Regressing the capacity criterion onto these 9 cues accounts for 95% of its variance, leaving only 5% that is uniquely due to the nonlinearities in the capacity-estimating procedure. Hence the beta weights from this formula provide a reasonable approximation of the relative importance of the 9 cues in the prediction of capacity (see Table 3). The two dimensions that were not involved in the production of the criterion played relatively small roles in predicting it, as would be expected. The intercorrelations among the nine cues and the criterion are presented in Table 3.

Knowledge and Cognitive Control

In the absence of significant correlations between residuals (trivial values of C in the above equation) then $r_a = G\, R_e\, R_s$. Under these conditions G represents the engineer's knowledge because it indicates what the subject's achievement would have been if he had executed his judgment policy with perfect cognitive control (i.e., $R_s = 1.00$) and if the environmental task criterion were perfectly predictable from the cues (i.e., $R_e = 1.00$).

Cognitive control (Hammond and Summers, 1972; Hammond et al., 1975) is appropriately measured by R_s in the equation (and thus used in the CCI) since there was little evidence in this study of lack of fit of the linear model in either the intuition-inducing film strip presentation or in the quasi-rationality-inducing bar-graph presentation. In the analysis-inducing formula-construction situation, however, it is important to note that the engineers' analytical judgments are produced by formulas; there is no "error" in the sense of random variation about a policy, as occurs in the intuitive and quasi-rational modes, because the formula produces the answers deterministically. Thus, in the analytical mode, R_s, the measure of cognitive

control, equals 1.0, and G, the measure of knowledge, differs from r_a only because of R_e, the environmental unpredictability--a factor that is independent of the engineer's behavior.

Using R_s to measure cognitive control thus ignores the fact that errors could be, and indeed were, made by the engineers in the analytical mode. Errors were made in constructing formulas, rather than errors in executing judgments. The measures of cognitive consistency in the Lens Model Equation do not take account of this type of error.

A subject's cognitive control in the analytical mode can, however, be ascertained by a careful review of his verbalized intentions (transcribed) of what his formula should be and the formula he actually constructed. This step results in two formulas for each engineer: the one presented to the researcher, the other constructed by the researcher to reflect the engineer's intentions. The correlation between the answers produced by these two formulas provides a measure of the discrepency between what was intended and what was executed; thus it is a measure of cognitive control comparable to the measure employed in the intuitive and quasi-rational modes.

APPENDIX C

Capacity Formula

Two methods for determining the vehicle-carrying capacity of a section of highway are given in the Highway Capacity Manual (Highway Research Board, 1965). Because both of these methods are in common use and are accepted in courts of law, their average was used as the criterion in our analysis. They differ in how they account for the effect of hills on the highway's capacity -- one uses information about the average grade, given in terms of the general terrain the road traverses, and the other takes a "bottleneck" approach and considers the effects of the steepest grade encountered in the stretch of highway. Both methods take into account lane width, lateral clearance to the nearest obstruction, the number of sides that obstruction is on, and the traffic mix, i.e., the percentage of trucks. The first method additionally takes into account the terrain (categorized as plains, rolling or mountainous, with the categorization determined by the average grade); the second method additionally uses measures of the length and angle (measured in percent rise, i.e., the tangent) of the steepest grade.

These methods are embodied in tables in the Highway Capacity Manual which are based on a large body of empirical research by traffic engineers.

The capacity procedures in the Highway Capacity Manual predict the capacity with the formula:

$$C = 2000 * W_c * T_c$$

where W_c and T_c are determined by tables. In both the Terrain and Steepest

Grade procedures, W_c is given by a table which is well fit by the following formula:

$$W_c = 1.64 - 0.256*LWIDTH + 0.0159*LWIDTH^2 + 0.0012*LWIDTH*LATCLEAR - 0.00918*LWIDTH*SIDEOBS + 0.000523*LWIDTH*LATCLEAR*SIDEOBS^2$$

In the Terrain procedure, T_c is given by a table which is well fit by the following formula:

$$T_{c(terr)} = 0.286 - 0.00817*TERRAIN^2*TRAFMIX - 0.00041*TERRAIN*TRAFMIX^2 + 0.000365*TERRAIN^2*TRAFMIX^2$$

In the Steepest Grade procedure, T_c is given by the formula:

$$T_{c(sg)} = \frac{100}{100 - TRAFMIX + E_t*TRAFMIX}$$

where E_t is defined by a table which is well fit by the following formula:

$$E_t = - 10.355 - 11.833*LSGRADE + 4.161*ASGRADE + 7.449*ASGRADE*LSGRADE + 0.705*LSGRADE*ASGRADE^2 - 0.286*ASGRADE^2*LSGRADE^2$$

Thus, when we take the mean of the Terrain and Steepest Grade capacities, the capacity used in this study is expressed by this formula:

$$C = 2000*W_c*((\frac{T_{c(terr)}+T_{c(sg)}}{2})$$

The fact that the Highway Capacity Manual is currently under revision would suggest that these are not perfect measures; however, they were the standard in effect at the time the study was done.

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